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An empirically-tested overlap between indigenous and scientific knowledge of a changing climate in Bolivian Amazonia

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Abstract

Existing climate data for the Bolivian Amazonia rely on observations from a few sparse weather stations, interpolated on coarse-resolution grids. At the same time, the region hosts numerous indigenous groups with rich knowledge systems that are hitherto untapped in the quest to understand local climate change. Drawing on an empirical dataset of climate change observations by an Amazonian native society, we assess the potential use of indigenous knowledge for complementing available climate data. We find indigenous observations to be robustly associated with local station data for climatic changes over the last five decades. By contrast, there are discrepancies between gridded climate data and both indigenous observations and local station observations. Indigenous knowledge can be instrumental to enhance our understanding of local climate in data-deficient regions. Indigenous observations offer a tool to ground-truth gridded descriptions of climatic changes, thereby making adaptation strategies more robust at local scales. We contend that the use of indigenous knowledge could help to assist the climate interpolation process and address the prevailing uncertainties in local assessments of climate change.

Keywords: climate data; ethnoclimatology; ground-truthing; indigenous observations; interpolation; Local Environmental Knowledge.

Introduction

Most datasets currently used to describe past or project future climate change rely on spatially interpolated gridded data from a number of weather stations. With some geographically heterogeneous areas poorly covered, these interpolated data generally show lower performance and decreased reliability from global to local scales (Hijmans et al. 2005; Fernández et al. 2013). Moreover, climate data are being developed at the global level, with coarse spatial resolution (Bindoff et al. 2013; Flato et al. 2013). Since one of the normative uses of these datasets is to assess impacts at more localized scales, climate data are increasingly being downscaled to resolutions that are relevant for policy-making in general and adaptation planning in particular (Fowler et al. 2007; Maraun et al. 2010). However, the resulting downscaled products are constrained by the uncertainty of the coarse-scale data that drive them (including interpolation errors), as well as by the new uncertainties introduced by the downscaling techniques (Zou et al. 2010; Chen et al. 2011). Arguably for these reasons, the ability of gridded climate data to describe climatic changes at the local level has been widely questioned (Hawkins et al. 2009; Zou et al. 2010; Potter et al. 2007). Here we explore the potential for the use of indigenous knowledge to address the above challenges in local assessments of climatic changes. We contrast local observations of climate change held by indigenous peoples in Bolivian Amazonia with widely used metrics of climate change (Garcia et al. 2014) based on spatially interpolated gridded climate data for the past 50 years.

Partly in response to calls to explicitly address uncertainty in climate observations in areas such as Bolivian Amazonia (e.g., Soria-Auza et al. 2010), some authors are starting to use indigenous knowledge as a place-based tool to scrutinize local indicators of climate change (Hulme 2011; Smith 2011; Barnes et al. 2013). Local Environmental Knowledge (hereinafter LEK) is one of the multiple dimensions of indigenous knowledge: a cumulative body of knowledge, skills and beliefs held by a specific group of people, handed down through generations by cultural transmission (Berkes et al. 2000). LEK is a holistic system for understanding the world, embedded in the culture of a group (including local institutions) and borne from long periods of observation, experimentation and continued interaction between people and their environment (Berkes et al. 2000; Gagnon and Berteaux 2009). Researchers argue that, to remain effective, LEK requires that indigenous peoples remain close to the production of knowledge, through well-connected social networks and robust institutional frameworks (Gómez-Baggethun and Reyes-García 2013; Mistry and Berardi 2016). In line with this, place attachment and long-term time continuity in resource use enable LEK holders to recognize local indicators not only of weather, but also of climate change (Monastersky 2009; Huntington et al. 2011; Klein et al. 2014).

Indigenous observations of climate change can therefore be considered a tacit and situated understanding of local climate change, reflecting a depth of embodied experience unlikely to be derived through structured and formalized processes (Fazey et al. 2005; Huntington et al. 2011; Klein et al. 2014). It has been argued that the strength of LEK systems lies in their long-term local-scale observations (Couzin 2007; Whipple 2008; Rosenzweig and Neofotis 2013). Not surprisingly, in the last decades, an increasing number of scientists have begun to tap into LEK systems as a starting point for their scientific studies (Reyes-García et al. 2015; Savo et al. 2016). Some studies have already attempted to compare scientific data with indigenous observations of climate change (Marin 2010; Klein et al. 2014). While informative, most of these works are limited in that: (a) they have been conducted on the basis of narratives rather than systematically collected individual knowledge data (e.g., Alexander et al. 2011); (b) they often compare indigenous and scientific data at different spatial resolution (e.g., Chaudhary and Bawa 2011); and (c) they have focused almost entirely on the Arctic and Himalayan regions (e.g., Vedwan and Rhoades 2001; Couzin 2007). Due to this relative lack of empirical work, the Intergovernmental Panel on Climate Change (IPCC) has recently called scientists to further develop the evidence base for the effectiveness of indigenous knowledge, particularly LEK (Niang et al. 2014). In a recent analysis of how indigenous knowledge is covered in the Fifth

Assessment Report of the IPCC, Ford et al. (2016) conclude that there is still little critical engagement between scientific and indigenous knowledge systems.

The use and/or application of indigenous knowledge to advance climate science is still largely lacking in tropical regions such as Bolivian Amazonia (Savo et al. 2016). Yet, the intricate relationship between Bolivian native Amazonians and their surrounding environment has resulted in detailed bodies of LEK, including ethnoclimatological knowledge, which are at the basis of their subsistence practices (e.g., Reyes-García et al. 2003, 2013; Cámara-Leret 2014). Moreover, this knowledge is often relatively independent from the scientific discourse on anthropogenic climate change, which remains still largely inaccessible in many areas, particularly in indigenous territories (Fernández-Llamazares et al. 2015a). In other words, indigenous observations of climate change are most probably conferred to local manifestations of such phenomenon and based on their LEK. Here, we: (a) empirically investigate if indigenous observations of climate change by native Bolivian Amazonians are consistent with scientific knowledge; and (b) whether consistency is higher for individuals with higher levels of LEK.

Theoretical background

In this article, we use the term '*indigenous knowledge of climate change*' as a leading analytical concept. Here we draw on Berkes' (2009) approach and consider local observations of climate change as part of a larger system of indigenous knowledge, developed locally, and passed down through generations. These knowledge systems integrate local values with information from external sources, as well as experiential and belief systems (Rudiak-Gould 2014; Pyhälä et al. 2016). More specifically the definition used here is structured around five components: *direct observations of the environment, historical baselines, cultural and symbolic values, peer information,* and *external information (media, science, NGOs)*. These components are defined in detail in Table S1, according to the works of Houde (2007) and Orlove et al. (2010).

Whether indigenous peoples' experience of climate change can be considered as knowledge or as perception is still heatedly debated (Raymond et al. 2010; Rudiak-Gould 2014; Pyhälä et al. 2016). Conservation scientists and ecologists mostly use terms such as *LEK* in their quest to better understand changes in the ecosystem (e.g., Pan et al. 2016), often in relation to climate change (Hopping et al. 2016). Contrarily, studies on natural resource management and psychological prefer to use the term *local perceptions*, generally focusing on the tacit and perceptual components of any representation of the environment (Fernández-Llamazares et al. 2016; Pyhälä et al. 2016). Meanwhile, climatological studies have often structured their discourse around notions such as *local observations* and/or *local indicators* (Rosenzweig and Neofotis et al. 2013; Reyes-García et al. 2015), emphasizing the empirical dimensions of this knowledge. While all these terms differ from one another conceptually, in this article they are understood as part of '*indigenous knowledge of climate change*' in its broader sense. We subscribe to Yeh's (2015:3) claims that considering the experience of indigenous and local peoples as a form of knowledge '*should be a non-negotiable starting point for interdisciplinary "human dimensions" of global climate change research*'.

Methods

Study area

Amazonia is generally recognized as one of the world's emblems of global environmental change (e.g., Mahli et al. 2008; Espinoza-Villar et al. 2009). The Fifth Assessment Report of IPCC compiles unequivocal evidence of climatic changes in the Amazon Basin over the last six decades, such as increased decadal variability in rainfall and increased frequency of heavy rainfall events, floods and dry spells (Mahli et al. 2008; Marengo et al. 2009; Satyamurty et al. 2010). However, it has been argued that knowledge of climate change in Amazonia is geographically biased (e.g., Espinoza-Villar et al. 2009). Moreover, existing efforts to understand climate change in the region are crippled by the low degree of spatial coherence and certainty in climate data due to limited or low-quality climate records (Hijmans et al. 2005;

Soria-Auza et al. 2010). For example, while the spatio-temporal patterns of precipitation and temperature have been well documented in Brazilian Amazonia (e.g., Satyamurty et al. 2010), studies for the remaining 37% of the cross-national Basin are meagre. This is of concern for adaptation planning, particularly considering that most adaptation strategies are developed under the national level (Adger et al. 2005).

Bolivian Amazonia covers 12% of the Basin and hosts 31 native indigenous groups (Fig. S1in Online Resources) whose resource-based livelihoods are increasingly threatened by climate change (e.g., Fernández-Llamazares et al. 2015a,b; Ruiz-Mallén et al. 2016). Amongst these, we work with the Tsimane', an indigenous hunter-gatherer society mostly inhabiting a communal territory comprising ca. 400,000 ha of *terra firme* rainforests, known as Tsimane' Territory (Fig. S2). The climate of the region is thermotropical, with a rainy season from November to March and a dry season from April to October with punctual cold spells from June to August, when polar winds from the South Pacific sweep through the area (Fernández-Llamazares et al. 2015a).

According to previously published research, the Tsimane' rely on more than 40 ethnoclimatic indicators to track local changes in climate (see Fernández-Llamazares et al. 2015a). However, they do not have a term to refer to climate change as such; rather, they basically report long-term changes in terms of specific changes in traditional bioclimatic indicators (e.g., phenology), or in weather ('*tupudye'* '). To some extent, they could be well conflating climate change and weather variability in a single notion, although in many instances they report changes in weather that seem to be beyond anything seen since childhood. Many informants expressed that the weather has become unseasonal and extremely unpredictable. For example, the fructification time of the peach palm (*Bactris gasipaes*), a sacred plant in Tsimane' cosmology that marks the beginning of the annual harvesting cycle, is changing, making it increasingly difficult to know when the harvesting is set to start.

Despite being unaware of the scientific construct of '*climate change*', the Tsimane' generally refer to a number of climate anomalies, which they largely interpret as a result of both natural and supernatural forces, with intertwined arguments. For example, many Tsimane' link the changes in climate with forest logging, arguing that '*Trees retain the water and cool the forest*' or that '*There are less trees, and therefore less shade; that is why it is warmer now*' (Fernández-Llamazares et al. 2015a:314). The Tsimane' also interpret climate shifts in spiritual terms, using traditional myths and stories to explain observed changes. For example, many Tsimane' believe that supernatural deities control the environment (including climate), and consequently they associate changes in the frequency of extreme climate events with deities' punishments in response to disrespect to certain established cultural norms (e.g., felling more trees than allowed by the forest deities). Similarly, a number of Tsimane' myths (largely referred to as the eschatological myths) show human attitudes toward natural catastrophes that could potentially wipe out humans and other living creatures from the Earth (Huanca 2008). The use of the term '*tsäqui'* ' (or great danger) is recurrent in myths providing supernatural explanation of rapid climate shifts.

Climatic data

Climatic data were sourced from the TS3.22 gridded climate dataset (0.5º x 0.5º) available from the Climatic Research Unit (CRU), one of the most used databases in IPCC assessment reports and numerous scientific studies in diverse fields from agriculture to health and biodiversity (Harris et al. 2009, 2014). The CRU monthly climate surfaces are interpolated from monthly observational data from networks of weather stations, using thin-plate smoothing splines with latitude, longitude and elevation as independent predictors. Since its first version for the period between 1901 and 1995 (CRU TS 1.0; New et al. 1999), the dataset has been continuously updated with the incorporation of new data sources, the removal of poor-quality records or values, the use of improved independent predictors, the addition of new climate variables, and the expansion of spatio-temporal coverage (New et al. 2000; Mitchell and Jones 2005; Harris et al. 2014). Despite such improvements, the quality of the climate data for any given region continues to hinge on the density of stations, the quality and temporal continuity of the data recorded, and the topographical heterogeneity of the region, amongst other factors. For comparison with the global dataset, we also sourced observation data directly from local weather stations, without any interpolation treatment. We used data from the nearest local weather station of the Bolivian National Service of Meteorology and Hydrology (SENAHMI) in the town of San Borja.

We sourced four climatic variables from both the CRU dataset and the weather station: (a) monthly mean temperature; (b) monthly minimum temperature; (c) total monthly precipitation; and (d) number of rain days per month. We gathered data for 1963−2012, a period chosen to approximate the temporal focus of indigenous observations. To describe changes in the four climatic variables during the 50-year study period, we computed a set of climate change metrics (Garcia et al. 2014) for each cell (0.5º x 0.5º) across Bolivian Amazonia using regional gridded climate data, and in San Borja using local station climate observations. Metrics were selected that corresponded most closely to the questions in the interviews to the Tsimane'. For comparison with local observations of changes in temperature and rainy season precipitation, our first two climate change metrics analysed the gradual trends in annual mean temperature and in mean intensity of precipitation in the rainy season (October to April). As an indication of changes in the length of dry season, we analysed the temporal trend in the total intensity of precipitation in the dry season (May to September). Changes in the frequency of cold spells were assessed based on the trend in the mean of the monthly minimum temperatures of the cold season (June to August). Changes in both the length of the dry season and the frequency of cold spells would ideally be analysed using daily precipitation and temperature, respectively, but such data were unavailable for Bolivian Amazonia. All calculations were performed using the R programming language and environment version 3.01 (R 2010). Temporal trends were estimated using the Theil-Sen slope implemented in the *openair* package in R (Carslaw and Ropkins 2012).

Quantifying the occurrence of droughts and floods would require data at finer temporal resolution and additional climatic and other abiotic parameters. Notwithstanding, with the data available we were able to assess changes in the frequency of extreme dry and wet conditions, which are seen as proxies for the occurrence of droughts and floods, respectively. We followed three steps to analyse changes in the probability of occurrence of extreme climates. First, we divided our study period into two 25-year segments, and identified, for a given cell, the extreme climatic values of the first segment (1963–1987) as the 5^{th} or 95^{th} percentiles of the distribution of climatic values for that cell during the first segment. Second, we calculated the percentile of the distribution of values during the second segment that corresponded to a given extreme value. This percentile was interpreted as the probability that such extremes were exceeded. Third, to assess changes in the frequency of extreme climates, we subtracted the probabilities in the first segment from those in the second segment: positive values indicated increased probability of extremes in the second segment. We applied this procedure to monthly total precipitation values to obtain an indication of the frequency of droughts (5^{th} quantile) and floods (95^{th} quantile).

Indigenous observations of climate change

During 21 months (January 2012 to November 2013) we collected individual-level data amongst the Tsimane' (Fig. S2). These data included: (a) climate change observations; (b) local environmental knowledge; and (c) socio-demographic and economic attributes. We obtained Free Prior and Informed Consent (FPIC) from villages and individuals participating in this study and the agreement of the political organization representing the Tsimane'. This research adhered to the Code of Ethics of the International Society of Ethnobiology (ISE). The Ethics Committee of the Universitat Autònoma de Barcelona (UAB) approved the research (CEEAH-04102010; LEK Project 2015). Two datasets were used in this study. Dataset 1 includes panel data collected in two Tsimane' villages (N = 99 adults, ≥16 years old) over the course of 18 months of fieldwork. Dataset 2 includes cross-sectional data collected in 13 Tsimane' villages (N = 308; Fig. S2) over the course of three months of fieldwork.

To capture consistency with scientific records, we conducted individual structured interviews (Dataset 1) about all changes observed since decade of birth (hereinafter DOB; Fernández-Llamazares et al. 2015b) for six climate variables (temperature, precipitation in rainy season, length of dry conditions, frequency of cold spells, flood frequency and drought frequency; see Table S1 in Online Resources). Changes perceived were coded as increase, decrease or invariant. In the interviews, we often probed for the informant's views of normal climate conditions (both at present and with reference to the informant's childhood), attempting to incorporate as much as possible an understanding of the local range of natural weather variability. We then assessed the consistency of individual observations with scientific records by calculating the number of answers in which the individual observations of the six aforementioned variables were in agreement with the climatic trends calculated for the area, based on: (a) spatially-interpolated climatic values from the CRU TS3.22 dataset; and (b) records from the local weather station.

We also examined potential desensitization to change, or the likelihood of failing to observe local indicators of climate change (Simons and Rensink 2005; Fernández-Llamazares et al. 2015b). To do so, we conducted individual structured interviews (Dataset 2) about static *versus* dynamic observations of climate since DOB, in relation to four climate variables (temperature, precipitation, frequency of cold spells and flood frequency). Our index measures the number of times that the observation of each of the climate variables was static (that is, to what extent the individual was unable to observe local indicators of climate change). We acknowledge that the notion of change desensitization can be misleading and reductionist, given that it could also correspond to an accurate static perception of climate (which might be coded as desensitization, while actually representing an active observation of a climate not showing changes at the local level). However, our use of the term here is only exploratory and context-specific, given the local climate shifts documented in the study area (see Fig. 1 and 2). Moreover, the use of the term in this study should be interpreted in the light of previous works on local perceptions of environmental changes amongst the Tsimane', which have empirically shown the existence of blindness with regard to changes in wildlife and palm thatch availability (Fernández-Llamazares et al. 2015b, 2016). Given that there is substantial evidence of generational amnesia with regard to past ecosystem changes amongst our study sample, the use of the term '*potential desensitization to change*' is justified. However, we call for caution when applying the concept for studies not counting with prior documentation of this complex cognitive process.

Additionally, we constructed a composite measure of LEK related to hunting, medicinal plants and wild edibles, using data collected from three different methods for each domain (Reyes-García et al. 2016): an identification task, a self-reported skills questionnaire and peer ratings (Table S2). For Dataset 2, the construction of the LEK index was performed with shorter questionnaires and only for two knowledge domains (medicinal plants and hunting). We explored the intra-subject consistency of our measures by running a series of Pearson correlations of the different measures in the two and three knowledge domains, respectively. We further explored the internal consistency of our measures by calculating the Cronbach's alpha coefficient for each domain (Reyes-García et al. 2016). As we found internal consistency between our measures, we used principal component factor analysis to generate new composite indices with standardized values of our different measures (mean = 0, variance = 1), with our aim being to capture some of the complex multidimensionality of LEK. Moreover, we checked for collinearity between our LEK index and the other socio-demographic variables listed in Table S2 by calculating Variance Inflation Factor (VIF). Since our VIF values are not greater than 1.46, high collinearity is not expected and our measure of LEK can be considered fully independent from the other variables.

Controls in our models include sex, age, village of residence and fluency in the national language (Spanish). Additionally we created indices proxying education, integration into the market economy, and forest dependence for both datasets (the variables included in these indices are listed in Table S2; Reyes-García et al. 2016).

Data analysis

We assessed the association between consistency of climate change observations and LEK by running (a) a Poisson correlation and (b) a Poisson multivariate regression with consistency as dependent variable and LEK as explanatory variable, a set of controls and clustering by village of residence. As the Variance Inflation Factor (VIF) values were smaller than 1.5, we dismissed the possibility of strong collinearity between LEK and other variables.

To assess trends in the association between potential desensitization to change and LEK, we performed a hierarchical cluster analysis classifying interviewees according to their scores in the variables change desensitization and LEK levels. We used the Ward's algorithm as agglomerative technique (Fig. S3). Then, we used Kruskal-Wallis and Chi-square tests to characterize the groups obtained with the hierarchical cluster analysis according to socio-cultural and demographic variables. For all the statistical analyses we used STATA 12.1 for Windows (StataCorp 2011).

Results

Climate change in Bolivian Amazonia

Based on available coarse-resolution, interpolated climate data from the CRU, climatic trends for Bolivian Amazonia between 1963 and 2012 show extended variation across space and across multiple climate change metrics (Fig. 1). Decreasing mean annual temperature trends (Fig. 1a) and decreased monthly mean temperatures during the cold season (used as an indicator of frequency of cold spells, Fig. 1d) seem to be the norm across the region. By contrast, precipitation trends in the rainy season show more pronounced spatial variation, with increasing trends in the southeast and decreasing trends in the northwest (Fig. 1b). As an indication of the potential occurrence of floods, extreme wet conditions become more frequent in the central and northwest areas (Fig. 1e). At the same time, the frequency of extreme dry conditions, an indicator of the potential occurrence of droughts, shows a general increasing trend (Fig. 1f), while the total intensity of precipitation in the dry season seems to be increasing in all the central part of Bolivian Amazonia (Fig. 1c).

Notwithstanding the availability of coarse-resolution data, weather station density in Bolivian Amazonia is low (Fig. S4) and the climate records gathered are often incomplete. The database from CRU relies on a mere six stations out of 39 existing within Bolivian Amazonia (Fig. S5a-b). Although often capturing the general climatic trend (Muller et al. 2013), stations are disregarded by CRU due to poor-quality data, gaps in records, or incomplete coverage of the full period targeted (from 1961 onwards; Harris et al. 2009). Climate interpolations based on the selected six stations might thus not be able to capture all the regional heterogeneity. A case in point is the analysis of climatic trends for a cell in mid-Bolivian Amazonia that contains a local weather station (San Borja). For four out of the six climate change metrics, the trends estimated with CRU data for this cell are in clear contradiction with those calculated with the observation data from the given weather station (Fig. 2a-b).

Overlap between LEK and scientific records

Based on the half-degree resolution interpolated data from the CRU , the climatic trends between 1963 and 2012 for the region enclosing the Tsimane' Territory show decreased mean temperatures and, remarkably, no significant changes in either the mean intensity of precipitation in the rainy season or the length of dry conditions (Fig. 2a). Yet, these trends are inconsistent with those estimated from records from the local weather station of San Borja (Fig. 2b), which reveal a steady increase in temperature, a pronounced decrease in the mean intensity of precipitation in the rainy season, and an increase in the length of dry conditions for the same time period. In turn, most Tsimane' interviewed (N = 99) report climate change during the last four decades (Fig. 2c-d), including increased temperatures and overall drier conditions reflected in decreased precipitation and increased drought frequency (Fig. 2c). The local observations for the subsample of people with high levels of LEK (N = 50), including local experts, elders, and traditional healers, show an even higher group consensus on a decrease in precipitation, higher temperatures and a pronounced increase in the length of dry conditions, amongst other metrics (Fig. 2d).

Tsimane' observations are thus in higher accordance with the scientific records from the local station (Fig. 2b) than with the scientific records from the interpolated CRU dataset (Fig. 2a). Bivariate analysis suggests a positive and statistically significant association between individual LEK scores and the degree to which individual climate change observations are consistent with climatic data from the local station. In other words, the higher an individual's LEK, the more accordance we find between her/his climate change observations and the climatic trends calculated for the local station (Fig. S6a, r = 0.537, p = 0.000). By contrast, the association is negative when individual climate change observations are compared with trends calculated from the spatially-interpolated climatic values from the CRU (Fig. S6b, r = -0.757, p = 0.000).

The positive association between an individual's LEK and the consistency of her/his climate change observations with the local climate data is corroborated in multivariate regression analysis controlling for potential covariates (age, sex, fluency in the national language, village of residency, education, integration into the market economy and forest dependency; Table 1a-d). Here too, the association becomes negative when the consistency is measured in relation to spatially-interpolated values (Table 1e-h).

A hierarchical cluster analysis to address potential desensitization to change shows that people with higher LEK levels seem to be more immune to change desensitization than individuals with lower LEK levels (Table S3). To some extent, LEK seems to attenuate desensitization to climate change, with people with higher LEK being comparatively more change-aware than people with lower LEK.

Discussion

Most efforts to reduce uncertainties in climate change assessments have centred on improving modelling techniques and applying new mathematical processes (Kay et al. 2009). Yet, circumventing uncertainties rests also on improving climate data (Hijmans et al. 2005; Joseph et al. 2009). Although significant progress is being made to improve spatial coverage of climate data, with the launching of new weather observation sites and the development of high-resolution satellite-derived climate datasets (Joseph et al. 2009), many tropical regions still have poor station coverage (New et al. 2002). Gridded climate data for these regions is thus prone to interpolation errors and should ideally be used in conjunction with information on weather station location and cross-validation statistics as a means to qualitatively assess the accuracy of the interpolated data (New et al. 2002). However, global gridded climate data such as the CRU (Harris et al. 2014) and Worldclim (Hijmans et al. 2005) datasets, widely used in climate research as well as in many other sectors from agriculture, forestry and hydrology to biodiversity and health (Harris et al. 2014), are often used without questioning their accuracy for the study region (but see, e.g., Fernández et al. 2013). To reduce uncertainties, critical use of global datasets in climate-related research is needed. At the same time, the exploration of more data sources, including harnessing new disciplines and knowledge systems, is strongly encouraged to increase the precision and accuracy of existing climate datasets, particularly in the tropics (Rosenzweig and Neofotis 2013).

The results of this work show both connection and discrepancy between scientific data and indigenous knowledge of climate change. On the one hand, our work is arguably also the first to empirically show a significant overlap between indigenous knowledge and scientific records from weather stations matched at the same spatial scale of observation (Fig. S6). On the other hand, we find dissonance between indigenous knowledge and spatially-interpolated climate values, widely used in climate change assessments. We argue that this discrepancy could be due to different spatial resolution of the two bodies of data. While the Tsimane' observe the world at a landscape level (e.g., for subsistence purposes, they walk an average distance of 20 km; Cruz-Burga et al. 2013), climate data are obtained at a larger scale (e.g., the closer CRU station being at more than 100 km from the Tsimane' Territory). Our argument here is that, even if the sources of error in both indigenous and scientific knowledge were minimal (e.g., interpolation errors), we might still find observation differences, many of which can be linked to the fact that the scale of observation differs from one knowledge system to another.

A finer analysis revealed that not all indigenous observations of climate change are always well-suited to detect local climate change. Rather, the consistency of LEK with scientific records (both at local and regional level) is partly shaped by an individual's fluency in the national language, education, market integration and forest dependence (Table 1a-h). Although more research is needed to fully understand the effects of these complex and multifaceted factors on climate change observations, we contend that they might be possibly linked to LEK erosion. Recent work amongst the Tsimane' has shown that due to age-related change in perceptions and decreasing intergenerational passing of knowledge, LEK is increasingly jeopardized (Reyes-García et al. 2013; Fernández-Llamazares et al. 2015b). Consequently, desensitization to change might be on the rise, potentially distorting local people's observations of climate change and thus undermining local adaptive capacity (Smith 2011; Fernández-Llamazares et al. 2016).

There is increasing evidence that indigenous knowledge of climate change strengthens community resilience to respond to climate change impacts and to deal with disturbances under conditions of high uncertainty (Gómez-Baggethun et al. 2013; Hopping et al. 2016). In general, LEK provides considerable buffering capacity when dealing with climate change perturbations and risks (Thornton and Manasfi 2010; Ruiz-Mallén et al. 2016). However, when these processes are interrupted, obstructed or hampered, vulnerabilities emerge and the resilience of the system can be severely undermined (Ford et al. 2015; Herman-Mercer et al. 2016). In this context, accurate observation and understanding of climate change at the local is critical for enhancing local agency for adaptation (Fernández-Llamazares et al. 2015a,b).

Based on our results for Bolivian Amazonia, we advocate that indigenous knowledge is well-suited to fill gaps in instrumental records of climate change, for areas where climate data are meagre at best (Fig. S5b). Nevertheless, we also recommend caution when considering indigenous observations of climate change, since not all observations are well-suited to contribute to climate research. Filtering indigenous observations of climate change based on individual LEK levels is thus advisable. There are several possible tools to minimize sources of error when documenting indigenous knowledge. These include careful selection of participants (Davis et al. 2003), peer evaluation for a rapid assessment of individual LEK levels (Reyes-García et al. 2016), or community verification of data in focus groups or community assemblies (Gagnon and Berteaux 2009). Such measures, though not infallible, ensure a standard of credibility and validation of the information collected. Additionally, the careful development of interview questions so as to match the metrics of climate change under analysis (Fig. 2) constitutes a first step towards the development of a more systematic and critical analysis of indigenous knowledge of a changing climate. Moreover, we want to stress that no sector of an indigenous society should ever be ignored or dismissed as '*non expert*' in any sampling strategy on LEK research. On the contrary, we encourage scholars to make sure their sample accurately reflects the social diversity within communities (see Koster et al. 2016) and to employ participatory methods that are sensitive to the traditional forms of community validation of knowledge, such as experiential validation based on cultural norms, or expert peer evaluation of local knowledge (Tengö et al. 2014; Reyes-García et al. 2016). Our point is that critical evaluation of LEK data should be done taking a respectful approach to LEK-holders and without incurring in ethical pitfalls.

If regional climate interpolations were complemented with information on local climate change trends as observed by LEK holders, a greater proportion of local climate peculiarities, idiosyncrasies and anomalies could be captured in datasets based on interpolated data. Indigenous observations can provide information with higher resolution that can be used to assist in the downscaling of global data. Specific outcomes of practical and direct application (for example, production of geo-referenced datasets of LEK-based climate change observations; Fig. S5b) could be useful for the systematic ground-truthing of spatially-interpolated climate values, thus making climate change impact assessments and adaptation plans more robust at the local scale (Barnes et al. 2013; Niang et al. 2014).

The purpose should not be to assert one knowledge type as more valid than another (Mistry and Berardi 2016), but rather to use them in such a way that indigenous knowledge can contribute to the endeavours of climate change research, and that science, in turn, can help to inform adaptation efforts in areas inhabited by indigenous peoples. Ultimately, and ideally, the outcome will be a co-produced knowledge base (*sensu* Armitage et al. 2011). Yet, it is essential to take into account the social, situated and dynamic nature of LEK (Berkes et al. 2000). In order to expand the range of available knowledge, scientific and indigenous knowledge should not be validated against each other, but rather complemented within a Multiple Evidence Base (MEB) approach (Tengö et al. 2014). Attempts to portray a precise and measured picture of climate change within an acceptable range of evidence and agreement should consider indigenous observations of climate change as a valuable proxy for monitoring the accuracy of existing climate data, narrowing their geographic uncertainty and informing the interpolation and downscaling processes. Indigenous knowledge, through cumulative experience and oral history, can also complement time-series climate data to piece together regional climate history and provide more close-up diachronic information on climate baselines. However, more empirical work is needed to address the impediments of matching observations with station records at the same spatial resolution, but probably different temporal resolution (Whipple 2008). Such diversity of perspectives can further benefit knowledge generation, promoting synergies across knowledge systems and creating an enriched level of understanding (Tengö et al. 2014). Following on this, the appraisal of indigenous knowledge should not be interpreted as an anathema to science, but rather as an opportunity to catalyse more robust intercultural dialogues around climate change.

Conclusions

The results of this work reveal a significant association between indigenous observations of climate change and scientific records at the local scale in Bolivian Amazonia. As additional empirical tests of overlap in other geographical areas become available to the scientific community, as well as innovative ways to address uncertainty in indigenous observations (Smith 2011), the gaps between scientific inquiry and indigenous knowledge systems might gradually become bridged. In our opinion, such converging evidence challenges the dichotomization between indigenous and scientific knowledge that, in confining them to discrete categories, pits the one against the other. Future climate research will benefit by moving beyond simple validations of indigenous against scientific knowledge, and by focusing instead on fostering linkages between both knowledge forms, resulting in '*hybrid*' knowledge frameworks (Reyes-García et al. 2015).

We contend that future climate research will substantially benefit from new partnerships and collaborations with indigenous peoples to report local indicators of climate change in some of the world's most data-deficient regions. Yet, such efforts bring to the fore issues about intellectual property and control over information (Couzin 2007), which are beyond the scope of this article. In this context, the formulation of protocols and guidelines for a diligent and respectful use of indigenous knowledge for scientific endeavours remains a critical step (Huntington 2011). In addition, examining the ways in which discrepancy between and uncertainty within different knowledge systems can be addressed in such a collaborative research framework is an important avenue for further climate research (Whipple 2008; Klein et al. 2014). Indigenous peoples, as close observers of local climatic changes, could for instance engage with research projects and consortia to address knowledge gaps identified in IPCC scoping or in assessments of local climatic impacts, provided that the structures in which indigenous knowledge is used and applied are not only determined by science (Mistry and Berardi 2016).

Nonetheless, if such aspirations are to be reflected in practice, there is an urgent need to formulate strategic plans to document indigenous knowledge before it vanishes (e.g., Cámara-Leret 2014). Due to the cultural changes brought by globalisation, LEK is suffering worldwide decline at alarming rates (Maffi 2005; Reyes-García et al. 2013). Hence, exploring the promising new frontiers opened by indigenous knowledge is a pressing task in the climate research agenda for the forthcoming years. While specific to Bolivian Amazonia, our results are likely to be relevant at the global scale, given that the regions in the world with the lowest density of weather stations (Fig. S4) are generally inhabited by indigenous peoples with rich, detailed and, in many cases, threatened LEK systems (Maffi 2005).

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Figures

Fig. 1 Climatic changes in Bolivian Amazonia, 1963–2012. Theil-Sen slopes based on CRU gridded data (Harris et al. 2014) illustrating the temporal trends in mean annual temperature (a), mean intensity of precipitation in the rainy season (b), total intensity of precipitation in the dry season (c), monthly mean temperature of the cold season (d) and changes in the probability of extreme monthly precipitation (95^{th} and 5^{th} quantiles, e and f). Positive values indicate increasing trends or probabilities of extremes; negative values indicate decreasing trends or probabilities of extremes. The scales were defined using quantiles and reflect a gradient from blue (changes towards cooler or wetter conditions) to orange (changes towards warmer or drier conditions)

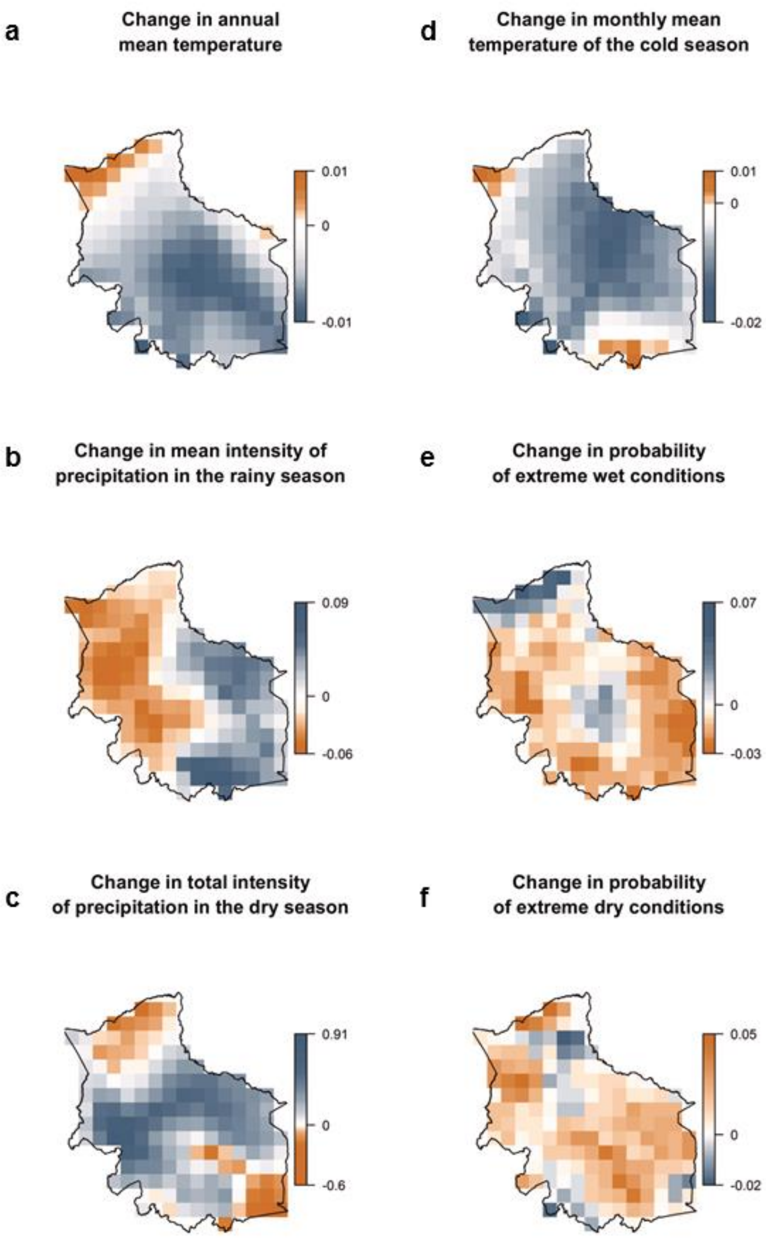
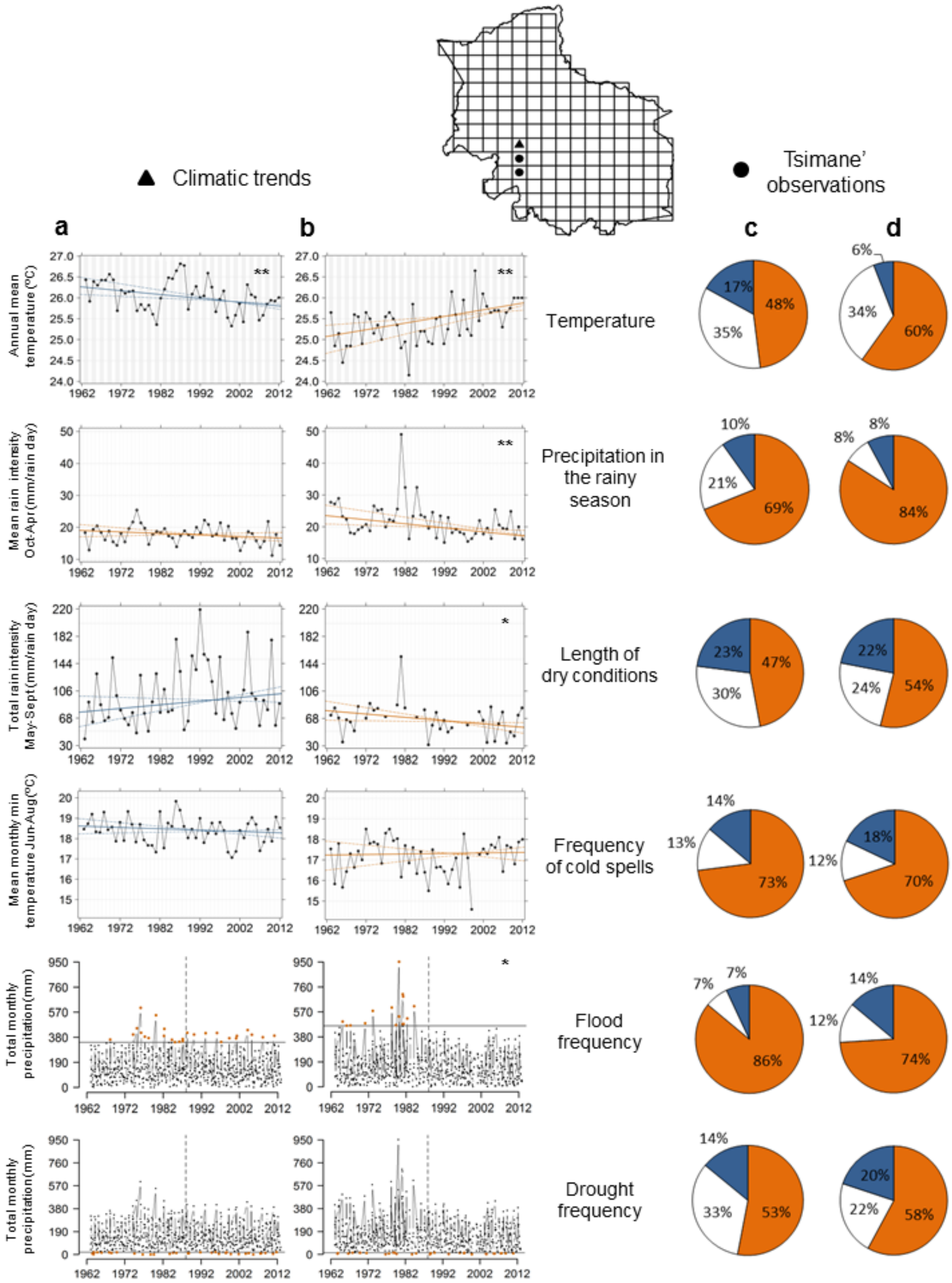


Fig. 2 Comparison of climate data with indigenous observations. For the grid cell containing the local station, climatic trends calculated with CRU gridded data (a) or weather station records (b) are compared with Tsimane' observations (proportion of the entire sample (N = 99, c) or LEK holders (N = 50, d) reporting increase, decrease or invariance in climatic parameters). Solid and dashed lines in scatterplots correspond to slope and confidence intervals at 95% (first three rows) and to baseline extreme and middle year (remaining rows), respectively. Blue, orange and white denote changes towards cooler/wetter, warmer/drier, or invariant. * p < 0.05 and ** p < 0.01. See Table S4 and Fig. S7 for more details on the climatic trends



Tables

Table 1 Poisson regression assessing the association between LEK and the consistency of the indigenous observations of climate change with both local station climate data and spatially interpolated climatic values

	Dependent Variable: *Consistency with scientific records*							
	Local station climate data				Spatially interpolated climatic values			
	Std. Model	Robustness Analysis			Std. Model	Robustness Analysis		
	a	B	c	d	a	b	c	D
Explanatory								
LEK	0.468 (0.032)**	0.386 (0.061)**	0.445 (0.072)**	0.464 (0.084)**	-0.692 (0.187)**	-0.602 (0.094)**	-0.685 (0.129)**	-0.651 (0.108)**
Control								
Age	0.004 (0.004)	0.001 (0.004)	0.005 (0.005)	0.005 (0.004)	-0.005 (0.011)	0.003 (0.012)	-0.006 (0.013)	-0.008 (0.012)
Sex (Male=1)	0.106 (0.002)**	0.202 (0.051)**	-0.022 (0.055)	0.008 (0.025)	0.242 (0.282)	-0.367 (0.192)	-0.025 (0.122)	0.075 (0.130)
National language (*totally fluent omitted*)								
Not fluent	0.116 (0.073)	----	----	----	-0.853 (0.142)**	----	----	----
Moderately fluent	-0.074 (0.109)	----	----	----	-0.175 (0.020)**	----	----	----
Education	----	-0.203 (0.002)**	----	----	-----	0.363 (0.066)**	----	----
Integration into the market economy	----	----	0.072 (0.026)**	----	----	----	-0.010 (0.104)	----
Forest dependence	----	----	----	0.000 (0.000)**	----	----	----	-0.001 (0.000)**
N	99	99	99	99	99	99	99	99

The table reports the Poisson regression coefficients with robust standard errors in parentheses. a-d, Regressions testing consistency with climate data from the local weather station of San Borja. e-f, Regressions testing consistency with spatially interpolated climatic values. All regressions are clustered based on the village of residency of the informants. * $P < 0.05$ and ** $P < 0.01$. For definitions of variables see Table S2.